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Methodology for Fire Following Earthquake Hybrid Simulation

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ABSTRACT

In this research, the hybrid simulation technique is discussed and further developed for application to investigate system-level fire load effects, referred to as hybrid fire simulation (HFS) or fire following earthquake hybrid simulation (FFEHS). It is a reliable and economical way to assess the performance of the entire structural systems exposed to fire and fire following earthquake (FFE), by combining numerical modelling and physical test. This paper presents the methodology and the framework to conduct real-time multi-hazard (post-earthquake fire) hybrid simulation of large-scale specimens considering the full interaction effects between the thermal and mechanical behaviour of the structure. In the proposed multi-hazard hybrid simulation framework, the element of the prototype structure exposed to fire is selected as the physical specimen (physical domain) while the remainder structure is numerically modelled (numerical domain). In the physical test domain of an FFE hybrid simulation, the test structure is first subjected to the earthquake, then, using novel HFS techniques, the structure is subjected to the temporal and spatial distribution of sequential fire loads. Heat transfer and thermomechanical analysis is carried out as the fire starts, during which the displacements and rotations of the numerical domain are transferred to the physical specimen and the measured restoring forces and temperatures of the physical domain are sent back to the numerical analysis. New OpenFresco and UT-SIM objects for beams/columns are under development to include both temperature and mechanical degrees-of-freedom with full compatibility on deformation as well as the thermal flux and force equilibrium at the interface between the physical and numerical domains.

Keywords: hybrid simulation, fire test, performance-based design, fire following earthquake, multi-hazards.

INTRODUCTION

Hazards may come in sequence, such as fire triggered by rupture of gas pipes after a major earthquake or subsequent aftershocks. In this potential combination hazards of earthquake and fire, the risk of collapse of the building systems is high, since earthquakes can have significant impact on the performance of the fire protection systems in buildings. Such extreme fire following earthquake events had been reported to have inflicted heavy casualties and economy losses during the San Francisco earthquake in 1906, Northridge earthquake in 1994 and Kobe earthquake Japan in 1995 [1]. Hence, further development on the design of structures against such devastating multi-hazard events is crucial.

The current practice of the structural fire design approach is the prescriptive method [2-3], which is to design structures following the code provisions to ensure the structural elements would remain structurally functional within a certain period of time when exposed to high temperature, without considering the interactions with other structural members. The understanding of the prescriptive approach is based on standard fire tests, in which a single structural component with idealized boundary conditions is subjected to elevated temperature represented by standard fire curves e.g. CAN/ULC-S101, ASTM E119, or ISO 834 [4-6]. Although the prescriptive code-based design is convenient and standardized, it does not take into account the global structural behaviour e.g. redistribution of loads, the deterioration of stiffness and increase of deformation as an entire structural system. To address these limitations, the new design method available in fire engineering which is capable of including the complete structural performance is the performance-based design [7]. Recently, there has been studies on establishing the framework for performance-based design of fire or fire following earthquake [8,9].

To assess the global structural performance, numerical modelling method can be adopted; however, the modelling becomes very challenging and the accuracy of the models can be questionable in terms of the complicated temperature dependent material properties, nonlinear behaviour in structures and complex structural configurations. As a result of these challenges in modelling, it is more realistic to carry out fire tests. A reliable measure to obtain the entire structural behaviour exposed to fire or fire following earthquake is to carry out full-scale fire tests, yet only a few cases have been conducted as pilot since they are prohibitively expensive and impractical as a routine testing method for the reason of the demanding requirements on the testing facilities and studies availability of such equipment as well as the full-scale prototype structures [10,11].

In light of the need for improving the design of structures against fire or FFE discussed above, it is necessary to develop a more efficient, accurate and economical testing technique alternative to full-scale fire tests to the better understanding on the performance of the complete structural systems under fire and FFE. For this purpose, a new fire testing approach referred to as hybrid fire simulation based on the recently developed methodology of hybrid simulation [12] in earthquake engineering is proposed, which combines physical testing and numerical modelling. An overview of the methodology of HFS is presented as follows. First, the fire scenario and fire load are defined for the prototype structure; then the part of the structure directly exposed to fire load is selected as the testing specimen for testing in a furnace (physical domain), while the remainder structure is numerically simulated (numerical domain). The thermal and mechanical response is transferred between the two sub-domains through an interface platform in real-time. In the physical test domain of HFS, in addition to the fire effects, i.e. the temporal and spatial distribution of the fire loads, the test specimen is also subjected to the gravity and lateral loads from the rest of the structure as determined from the numerical domain of the structure. After the fire starts, in each time step, the measured force and temperature from the physical domain will be fed back to the numerical simulation through the interface, and the finite element software will start the thermomechanical analysis to calculate the structural response and send the thermal and mechanical information at the connection back to the physical specimen; and then move on to the next cycle until the end of the test.

In the following, an overview of the previous research on hybrid fire simulation is presented. A new framework and the methodology of real-time multi-hazard (post-earthquake fire) hybrid simulation which includes full interaction effects for performance-based assessment of complex building structures are proposed. The gaps between the current state and future development on this subject are highlighted.

OVERVIEW OF HYBRID FIRE SIMULATION

Hybrid fire simulation has started to attract increasing attentions in recent years. However, there have only been limited number of studies on combining physical testing and numerical modelling in fire research. Table 1 shows a summary of previous research. The first hybrid fire simulation can be found in literature was reported by Korzen et al in 1999 and 2002 [13,14], the proposed framework is shown in Figure 1. In their studies, an 8-storey steel frame building was chosen as the demonstrating structure. One column was physically tested in the gas furnace at BAM (Federal Institute for Materials Research and Testing) in Germany and the rest of the structure was represented by a predefined idealized model of the rest of the structure as a constant axial stiffness. The axial displacements and forces at the interface were exchanged through a 6-channel control system in the laboratory. In 2010, Robert [15] at CERIB (Centre for Studies and Research of the Concrete Industry) in France conducted an HFS of a single-storey concrete frame, the physical domain was a concrete slab with three degrees-of-freedom controlled in total (one axial elongation and two rotational at the supports); whereas the numerical domain was represented by an elastic stiffness matrix. Later in 2012, Mostafaei [16,17] successfully tested a column in a 6-storey reinforced concrete building in a gas furnace at NRC (National Research Council Canada) in Ottawa through HFS shown in Figure 2. In his study, the numerical domain was simulated as a 2D/3D finite element model in a special purpose finite element software SAFIR [18]. The calculated axial deformations and forces at the interface of the numerical domain were exchanged with the physical domain in each time step. However, in this early HFS, the data transformation and exchange within the physical and numerical domains was not automated and required human interaction. The first fully computer-controlled hybrid fire simulation with a finite element model for the numerical domain was proposed by Whyte et al [19] in 2014, the framework is presented in Figure 3. In their research, a new OpenFresco [20] truss element with one temperature degree-of-freedom at each end node was developed, which can be adopted to realize one-way or two-way coupling between the sub-domains of the structure. The small-scale proof of concept HFS of a 2D elastic truss structure was carried out at ETH (Swiss Federal Institute of Technology) within the OpenSees [21] and OpenFresco frameworks. A similar test was carried out by Schulthess et al [22] using ABAQUS [23] and an interface server instead. The most recently published research work on HFS was by Wang et al [24] at University of Toronto in 2018. In their proposed method as demonstrated in Figure 4, fully automated and displacement control with proper error compensation scheme was realized and validated in a full-scale HFS through the UT-SIM interface platform [25].

There are other research works [26-31] carried out on hybrid fire simulation in a purely numerical environment, in which both the numerical and the physical domains are represented by computational models, incorporating with different control strategies and interface platforms.

It is noted, all the previous attempts on hybrid fire simulation discussed above typically do not consider the full interactions between the numerical and physical domains of the structure, because of insufficient number of mechanical and thermal degrees-of-freedom at the interface. Specifically, the mechanical degrees-of-freedom was limited to axial load in most previous studies [13, 14, 16-24]. In terms of the consideration on the thermal effects at the interface e.g. heat conduction between the heated and adjacent structural elements, Whyte el al. [19] adopted their newly developed element to send temperatures to the physical specimen, and Wang et al. [24] applied a previously generated time-temperature history of physical specimen on the numerical domain at the interface node. However, these two approaches can be adopted only when the structural members are not sensitive to the temperature distribution within the cross sections.

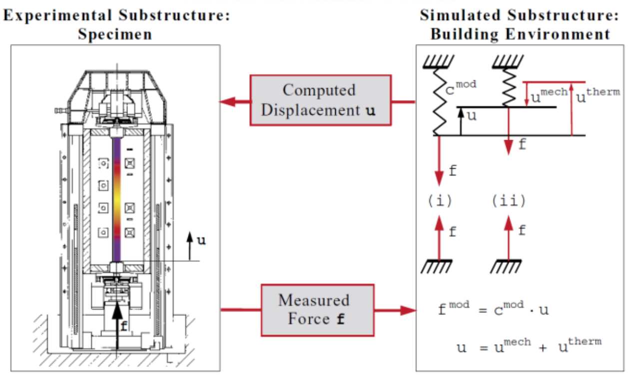

Figure 1. The HFS framework [14].

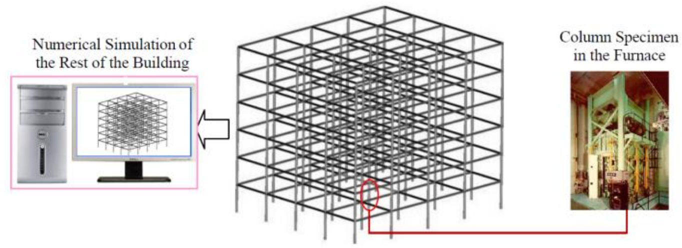

Figure 2. The HFS components for the 6-storey building [17].

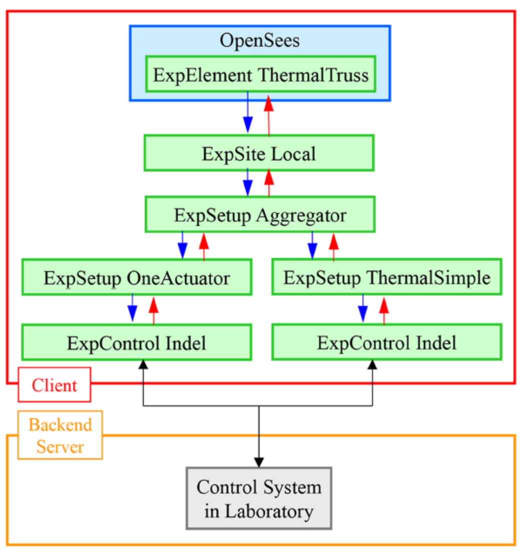

Figure 3. OpenFresco/OpenSees HFS Architecture [19].

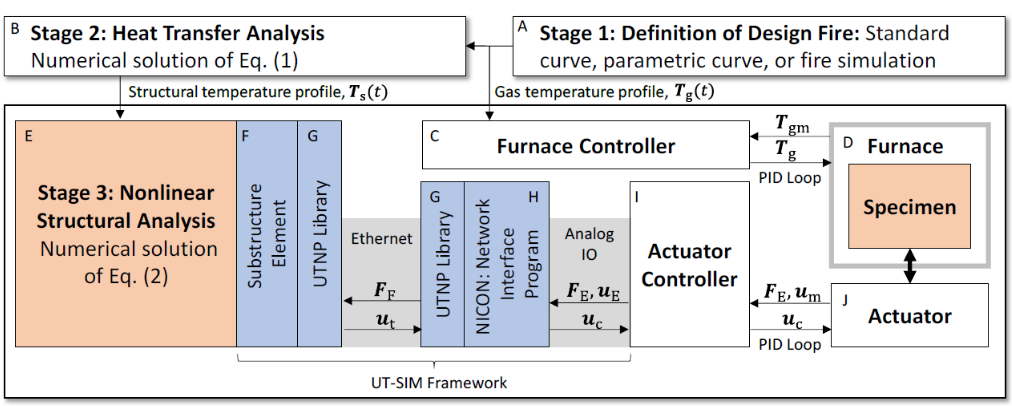

Figure 4. Stages of HFS [24].

Table 1. Summary of Previous Research on Hybrid Fire Simulation.

Previous Research	Structure	Testing Facility	Physical Domain	Interface	MDOF	TDOF	Numerical Domain	Heat Conduct to Adjacent Components
Korzen et al. (1999)	8-storey steel frame	Gas Furnace (BAM)	Single column	6-channel control system	1 (axial)	--	Constant axial stiffness	--
Robert et al. (2010)	1-storey concrete frame	Gas Furnace (CERIB)	Single slab	--	3 in total (1axial+ 2rotational)	--	Constant stiffness	--
Mostafaei (2012)	6-storey reinforced concrete frame	Gas Furnace (NRC)	Single column	Human interaction	1 (axial)	--	SAFIR 2D/3D (nonlinear)	--
Whyte et al. (2014)	steel truss	Electric Furnace (ETH)	Single truss	OpenFresco/New objects for truss element	1 (axial)	1	OpenSees/Standard (linear)	--
Schulthess et al. (2016)	steel truss	Electric Furnace (ETH)	Single truss	Server	1 (axial)	--	ABAQUS (user subroutine)	--
Wang et al. (2018)	4-storey steel frame	Gas Furnace (KIST)	Single column	UT-SIM	1 (axial)	--	ABAQUS (nonlinear)	Predefined time-temperature curve

Note: MDOF and TDOF represents the mechanical and temperature degrees-of-freedom considered at the interface node respectively.

METHODOLOGY FOR HYBRID FIRE SIMULATION

In the proposed hybrid fire simulation method within the framework of performance-based design in fire safety engineering, a key requirement in capturing the complete structural behaviour is to account for the full interaction effects. The full interaction effects between the two sub-domains, physical and numerical, include the heat transferred from the fire to the structures, heat conduction as well as the forces, displacements, rotations induced by the elevated temperature. In addition, it is also necessary to update the boundary conditions in both the numerical and physical domains in real-time throughout the hybrid fire simulation to ensure full compatibility at the interface. The full interaction effects can be realized by coupling of the thermal analysis, mechanical analysis with thermal loading, high-performance testing facilities, and sufficient data exchange in the interface platforms. The details of the HFS protocol considering full interaction effects are presented in the following.

Thermal analysis

The thermal analysis aims at solving for the temperature profile in the structures exposed to fire, including (1) the convective and radiative heat transfer analysis from the fire to the surface of the structures by computational fluid dynamic (CFD) software; and (2) the conductive heat transfer within and among the structural elements using finite element analysis (FEA). In the proposed new framework, a one-way coupled analysis approach between CFD and FEA is adopted [30].

In the performance-based analysis, fire scenarios are chosen according to a number of factors e.g. the fuel type, the fuel consumption, the ventilation condition etc., which can be either represented by parametric fire curves or simulated by CFD software e.g. FDS (Fire Dynamic Simulator) [32] developed by NIST. Recognizing the complicity of the fire dynamic phenomenon in the convective and radiative heat transfer from the fire same to the surface of the structures, it is more accurate to use the fire load curves generated by CFD simulation. Here as an assumption that the structural responses do not affect the fire load, e.g. no total collapse occurred during the analysis, a one-way coupled analysis between CFD and FEA can be used. After obtaining the temperature/heat flux profile at the surface of the structural elements by CFD, the conductive heat transfer is carried out to solve for the temperature gradient in the sections of the structural members using finite element (FE) software, e.g. SAFIR, OpenSees for Fire [33], ABAQUS etc.

Mechanical analysis with thermal loading

In the mechanical analysis with thermal loading, typically by using specialized FE software packages specially developed for fire engineering, the structural responses under the static and thermally induced mechanical loading are calculated. The mechanical analysis is carried out sequentially after the thermal analysis based on the previously generated temperature profile in the structure. In the mechanical structural analysis within the proposed framework, the structure is subjected to the constant gravity load as well as the time variant forces, moments and the temperature gradient introduced from the physical domain at the interface node. The responses of the structure are calculated in the thermal-mechanical analysis are fed back to the physical specimen for the next cycle of HFS of the structure.

Testing facilities

The National Research Council Canada (NRC) has conducted extensive fundamental research and innovative investigation on structural behaviour in fire. The NRC fire laboratory has a number of unique high-performance furnaces including a column furnace, a wall furnace and a floor furnace, which can carry out large-scale fire tests. The high-performance column furnace at NRC has the unique capability of conducting high temperature fire tests of full-scale specimens under controlled axial, lateral and rotational degrees-of-freedom and applied forces and moments. It is one of the best large-scale furnaces in the world that can carry out hybrid fire simulation with full thermal and mechanical interaction effects.

Interface platforms

To include the full interactions for performance-based design as mentioned before, it is necessary to have the capability of sufficient information exchange and communication between the numerical and physical domains during the hybrid fire simulation. The implementation in the proposed framework is through the UT-SIM and OpenFresco interface platforms, which provide standard data exchange protocols. However, both of these middleware platforms are originally developed for conducting seismic hybrid simulation for earthquakes, which only requires force and displacement information exchange between the numerical and physical domains. In order to conduct hybrid fire simulation, new thermal objects with the capacity of exchanging temperature gradient information are under development.

Process of hybrid fire simulation

The procedures of carrying out hybrid fire simulation, as shown in figure 5, are described as follows:

Step 1: define the fire scenario and obtain the fire load for the entire structure as shown in Figure 5(a), by carrying out fire simulation in CFD software;

Step 2: conduct the thermal analysis with gravity load for the complete structure at ambient temperature to determine the initial mechanical boundary conditions i.e. axial and lateral displacements, moments, for the numerical and physical domains at the interface, as demonstrated in Figure 5(b);

Step 3: impose the previously calculated initial loads on both the numerically modelled structure and the test specimen in the fire test furnace;

Step 4: initiate the fire load to the test specimen in the furnace as shown in Figure 5(c);

Step 5: measure the thermal and mechanical responses at the interface node between the numerical and physical parts of the test structure at the end of the time step;

Step 6: apply the obtained nodal temperature gradient and the mechanical loads (transferred through the interface platform) on the numerical structure at the same degree-of-freedom, then sequentially carrying out the thermomechanical analysis to calculate the structural response;

Step 7: impose the obtained structural response of axial, lateral displacements and rotations at the interface node from previous step of the physical specimen;

Step 8: repeat Step 5 to Step 7 until the end of the temperature-time history, or the cooling process.

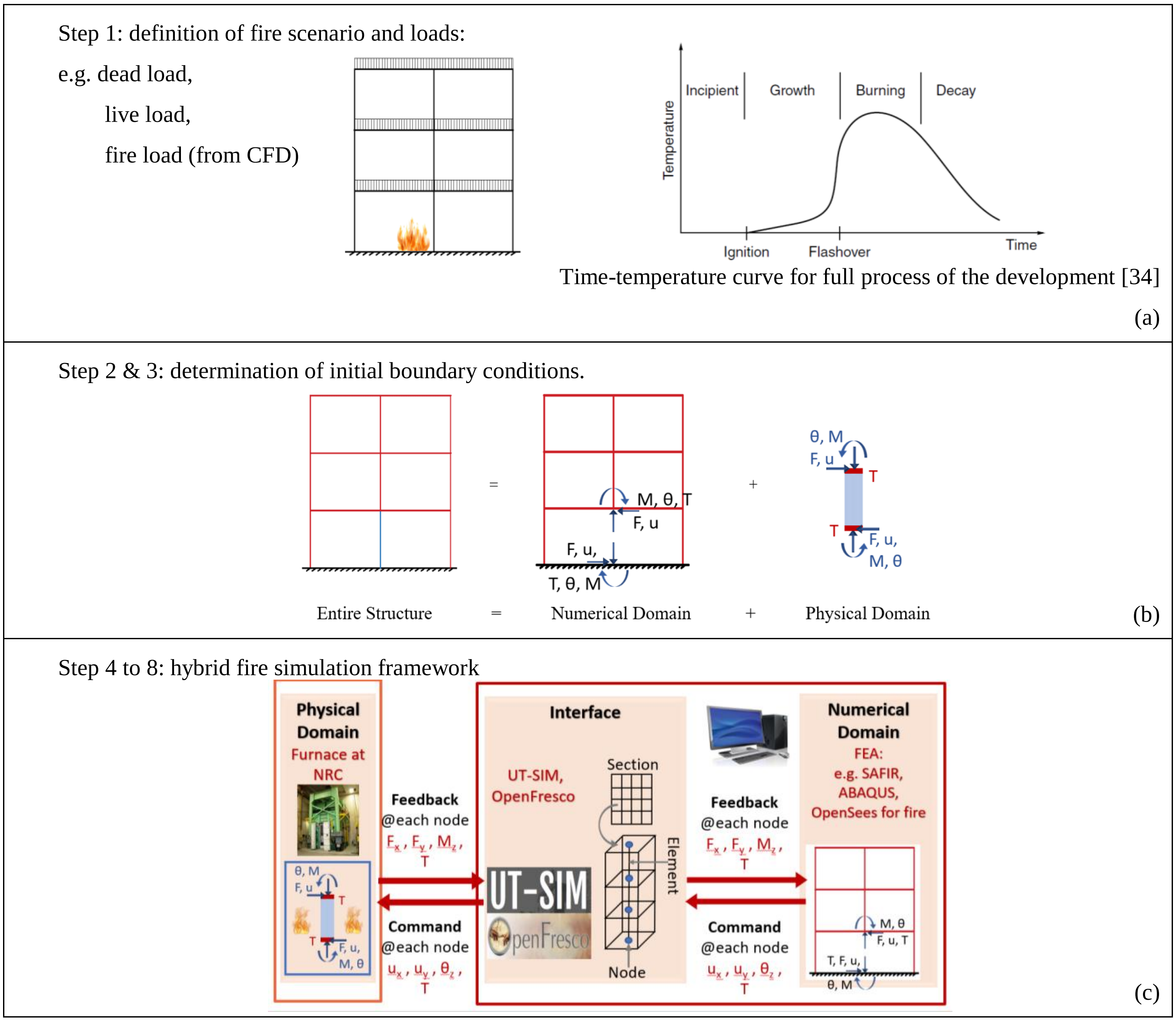

Figure 5. Process of hybrid fire simulation.

METHODOLOGY FOR PROPOSED FIRE FOLLOWING EARTHQUAKE HYBRID SIMULATION

The proposed hybrid fire simulation method can be extended to evaluate full-scale system-level structural response of existing buildings or new constructions in fire following earthquakes. This allows the evaluation of the effect of earthquake damage to active and passive fire protection systems. In the novel multi-hazard hybrid simulation framework, the regular hybrid simulation is carried out, after which the earthquake damaged structure is exposed to fire using the proposed HFS technique. The most important stage is to account for the cumulative damage in the entire structural system under the earthquake and fire loading sequence. In the physical test domain, the seismic damage in the test specimen can be obtained directly after the hybrid simulation for earthquake. However, in the numerical domain of the structures, the earthquake damage state in the model need to be specially saved as the initial condition in the sequential analyses of structure in fire. There are some research works focus on enabling this kind of modelling capacity between some finite element software e.g. between OpenSees and OpenSees for Fire [35], OpenSees and SAFIR [36].

FUTURE WORK

The future works mainly focus on the implementation and validation of the proposed multi-hazard hybrid simulation framework by conducting real tests in the laboratories between Carleton University and National Research Council Canada. In addition, this novel testing technique has the potential to include fire spread scenarios by introducing multiple furnaces at NRC and other geographically distributed testing facilities.

SUMMARY AND CONCLUSIONS

By applying hybrid simulation methodologies, previously developed for earthquake engineering applications, to fire simulation and fire-after-earthquake applications, more cost-effective assessments of complete structural systems may be conducted. A proposed methodology and framework for such tests are presented in this paper. New objects in the interface platforms i.e. OpenFresco and UT-SIM are under development to capture the full interactions between the numerical and physical domains of the structure under the thermal and mechanical loading. With the potential capability of considering fire spread in structures, this novel multi-hazard hybrid simulation technique can be seen as a promising approach to the better understanding on the global structural behaviour under multiple hazards, to assist the development of multi-hazard as well as performance-based design.

Additional works in various fields are suggested to improve the fire following earthquake hybrid simulation technique: enhancement on the coupling between CFD and FEA; bridging earthquake-fire coupled structural analysis among different finite element software; development on the temperature dependent material models e.g. timber; and improving the error compensations in the control systems.

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